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THE MODE OF ORIGIN OF COAL[1]

EDWARD C. JEFFREY
Harvard University

The question of the manner of formation of coal has divided geologists for over a hundred years and the problem is still disputed, although at the present moment the weight of geological opinion inclines in one direction. Where so much difference of opinion has existed for so long a period, new evidence is obviously much to be desired. The current views as to the origin of coal are based mainly on a consideration of the stratigraphic evidence other than that supplied by the coal alone. For example, much importance has been attached to the presence of underclays beneath the coal beds, as evidence of the existence of an ancient forest soil. Likewise a considerable amount of importance has been attached to the existence of Stigmarian and other root or rootstock systems in the substratum beneath the coal. Comparatively little evidence has been derived from the consideration of the coal itself. Where such evidence has been available it has been of a contradictory nature. For example, certain coals rich in bituminous matter, such as cannels and the like, obviously present in their organization strong resemblances to the muck formed in the bottoms of modern lakes; that is, they consist, to a very large extent, of the remains of spores and pollen. In other cases, much more rare, concretions have been found in the coal, containing quantities of often well-preserved vegetable remains. These remains are of such a character and are related to one another in such a way, that their clearest modern representative is the peat of existing peat bogs. The two kinds of evidence derived from petrified coals on the one hand or from the persistent structures in unmineralized coals on the other appear to justify diametrically opposite views as to the conditions of coal formation. Similar contradictions apparently present themselves, when the strata below (underclays, etc.) or above (roof strata) the actual coal beds are considered. We have as a consequence the two opposed schools of opinion in regard to the origin of coal. The hypothesis which homologizes the coal bed with an existing peat deposit is known as the autocthonous or *in situ* theory. On the other hand, the view that coal represents an accumulation by floating and sedimentation in the bottom of open lakes or lagoons is known as the transport or allocthonous hypothesis. The evidence for and against these two opposed views has recently been so admirably summarized by Professor John J. Stevenson in his *Formation of Coal Beds* that it appears unnecessary to refer to the subject further at this time.

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[1] *Contributions from the Phanerogamic Laboratories of Harvard University, No. 67.*

The purpose of the present communication is to emphasize the importance of the study of the coal itself, in connection with any views as to its composition and mode of origin. The investigation of coal by means of the microscope has presented many difficulties, chiefly because of the opacity and texture of the coal itself. The methods which have been successful in the case of other minerals have not given satisfactory results in the case of coal. The thin ground sections of the mineralogist and petrologist are of little value when the material investigated is coal. If the ground sections are made thin enough to show all of the structural features, these are destroyed by the abrasive effect of the process on the comparatively soft and friable substance of the coal itself. The writer has had considerable experience in investigating the remains of fossil plants in a carbonized condition, a state of preservation which has hitherto been neglected in favor of petrified material. Material in a mineralized condition of preservation is, however, comparatively rarely available, while carbonized vegetable remains are often abundant. A modification of the writer's methods in the case of carbonized Mesozoic plants has been developed as the result of a long series of experiments, and it is now possible to secure satisfactory thin and transparent sections on the microtome of practically all kinds of coals. Obviously this possibility put the question of coal composition and mode of formation on an entirely new footing, as it is now possible to investigate these subjects satisfactorily from the standpoint of the organization of coals of various geological ages in different parts of the world. The writer has examined coals derived from regions as far apart as Alaska and Patagonia, Dakota and Texas, Washington and Virginia, Great Britain and Japan, Sweden and Tasmania in geographical separation, and in stratigraphic distribution from the Devonian to the Miocene and the present epoch. The results of these investigations have been satisfactorily uniform. We are now apparently in the position to judge of the great problems of coal formation from the all-important aspect of the organization of the coal itself. In other words, we are no longer compelled to infer the nature of coal from the conditions of deposit of the surrounding strata, which may have been laid down under very different circumstances, but we can reach definite conclusions from the structures revealed by the coal itself under the microscope.

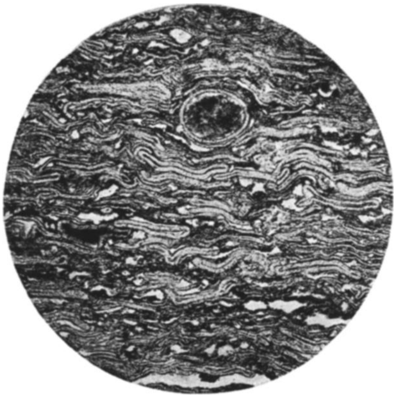

FIG. 1

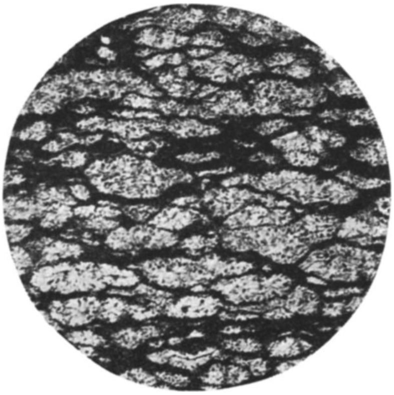

FIG. 2

Reference has already been made to the fact that certain coals, containing large quantities of spores, are generally admitted to have been formed, not on land as the case with peat, but as sedimentary deposits in open water. Fig. 1 illustrates a notable carbonaceous deposit of this type, namely tasmanite. In the upper part of the figure one spore still retains its rounded contour, but the spore material as a whole, which is very abundant, is represented by the collapsed spore coats, inclosing a linear cavity. Fig. 2 shows the structure of another type of spore coal, an oilshale from

Australia. Here all the spores have collapsed and have rough alveolar exteriors. A remarkable feature of oilshales is the very large amount of spore material present in them, a condition correlated directly with their rich petroleum content when subjected to distillation. A curious error of interpretation has been made in regard to oilshales, bogheads, or bituminous schists, as they have been variously termed. Their structural elements have been regarded by Renault, Bertrand, and Potonié as the remains of delicate gelatinous algae. The present writer, by the improved methods already referred to, has secured evidence that the structures in question are the very rough spores of extinct fernlike cryptogams.[1] It is clear, further, that they cannot be anything of so delicate a nature as algae, since highly modified wood is frequently found in the same matrix with them. It is obvious that gelatinous algae would have quickly been obliterated by influences so powerful as to eliminate the structural organization of wood.

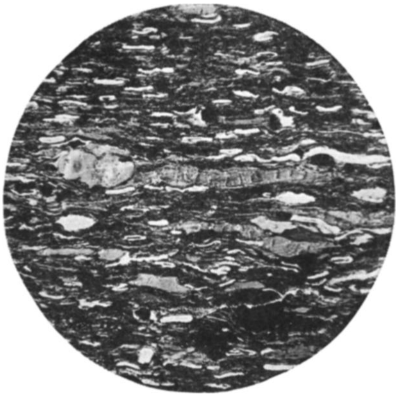

Fig. 3

Fig. 3 shows the organization of Kentucky cannel. Scattered throughout the matrix are light bodies which are yellow in the coal itself. These represent spores. They are inclosed in a darker matrix which in some cases reveals lighter, somewhat undulating or crinkled bands or particles. These structures are brown in color in the coal and represent the remains of wood. A large stripe of this kind runs nearly across the illustration. Cannel owes its highly bituminous character to the presence of large quantities of spores, just as is the case with oilshales and tasmanite. Since the spore material is less pure than in the former types of coals, the bituminous matter is less and the distillate of petroleum is correspondingly reduced in amount.

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[1] "The Nature of Some Supposed Algal Coals," *Am. Acad. Arts and Sci.*, XLVI (December, 1910).

It is universally admitted that all three types of coal shown in the illustrations are formed as a result of water deposit. It will be convenient at this stage to consider rather rare types of coal which show considerable evidence of being derived from ancient peat beds. Coals of this organization represent old swamps skirting the sea and correspond, with certain necessary allowances made for the difference of vegetation in the Paleozoic, to our existing tidal mangrove estuaries. They are usually designated on this account as paralic (*paralisch* of Naumann) coals. In some coals of this type from Great Britain, Westphalia, and the Donetz coal field of Russia concretions have been found known as coal balls. A very good account of these structures, particularly for the English examples, was published, not long since, in the *Philosophical Transactions of the Royal Society of London.*[1] Our Fig. 4 shows the structure of a coal ball from the Westphalian coal field in Germany, which I owe to the courtesy of the Geologische Landesanstalt of Prussia. In the lower part of the figure is the crushed stem of a young calamite and the rest of the area is made up of less recognizable remains. Fig. 5 illustrates the appearance of the coal adhering to the outside of the same coal ball. It has been shown clearly by

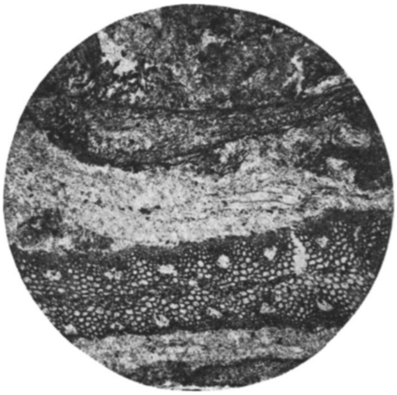

FIG. 4

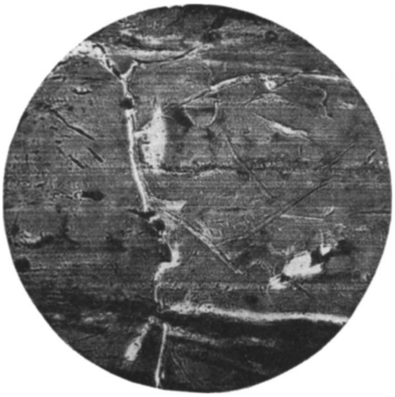

FIG. 5

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[1] Stopes and Watson, "On the Present Distribution and Origin of the Calcareous Concretions in Coal Seams, Known as 'Coal Balls,'" *Phil. Trans. Roy. Soc. London*, Series B, Vol. CC, 167–218.

Stopes and Watson that true coal balls are formed *in situ* in the coal by local impregnation of the original peaty substance with lime or magnesium carbonate or both. The mineralized portion of the peat retains its structure, while that which has not been impregnated is completely devoid of definite organization when transformed into coal. If all coals were derived from ordinary peat they would present the same homogeneous organization as shown in our Fig. 5, since wood and similar formations have their structure obliterated when transformed into coal. In this respect peaty deposits present a marked contrast to the lacustrine mucks which have been the forerunners of cannels and oilshales. The spores and similar cutinized structures are the only remains of plants, which in general do not become obliterated in organization when passing into coal. Only petrification can save ordinary peat in the long run from the complete obliteration of its original vegetable constituents.

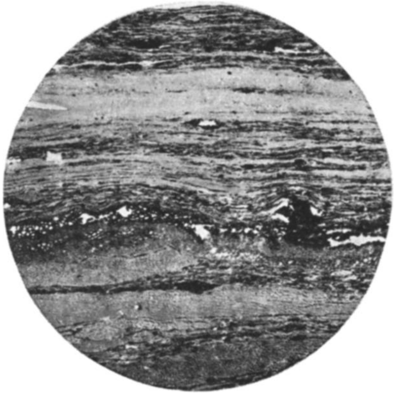
FIG. 6

It is now possible to consider with advantage the commoner types of coal, those which occur in greatest abundance in all parts of the world where coal deposits exist. Fig. 6 illustrates a coal of this ordinary bituminous type from Illinois. It is at once clear that the structure is not homogeneous as in the Westphalian coal shown in Fig. 5. Running across the figure is a dark band of "mother of coal" or mineral charcoal. This represents wood which was charred by fire before it entered into the substance of the coal. Mother of coal, inappropriately so called, represents the only woody constituent of ordinary coals which retains its structure. Very often the woody elements are in a perfect condition of preservation and the nature of the trees which produced them can be diagnosed. In addition to the dark band of mineral charcoal or mother of coal, there are other narrower dark stripes in the coal, as well as lighter-hued more homogeneous bands. The latter correspond to highly modified wood. The nature of the others can best be understood from Fig. 7. This represents a portion of the last figure, much more highly magnified. The dark stripes are now seen to contain numbers of very light-colored bodies or spores.

Fig. 8 shows the organization of a very highly bituminous coal from Kentucky. The crenulated bands corresponding to layers of modified lignitic substance stand out very clearly in this illustration. Between the woody or lignitoid zones are darker stripes variegated with light linear bodies. The latter are compressed spores. Fig. 9 shows a part of the foregoing highly magnified, and the canneloid nature of the darker bands alternating with the lignitoid layers can now be clearly ascertained.

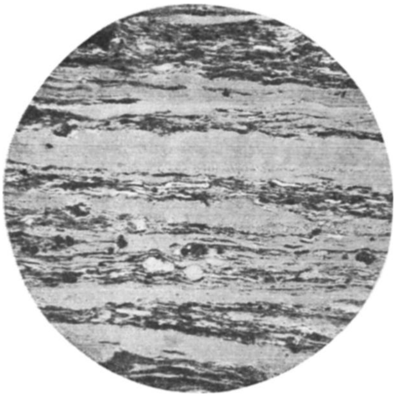

FIG. 7

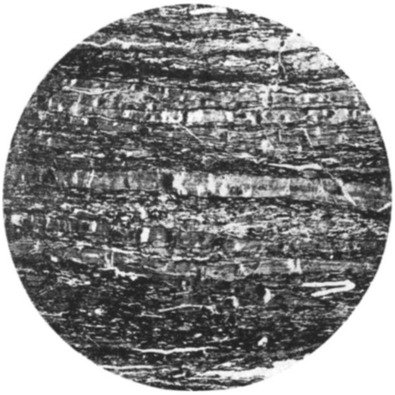

FIG. 8

Further examples of coals may now be considered. Fig. 10 shows the structure of a bituminous coal from European Russia. Clearly it is largely composed of spores. Through the courtesy of M. Zalessky of the Comité Géologique of St. Petersburg, I have had the opportunity of examining a considerable number of coals from European as well as Asiatic Russia, with similar results as regards organization (except of course the coals of paralic origin). Fig. 11 reveals the structure of non-coking bituminous coal from Indiana. The conditions presented are the same as in the case of the Illinois coal, with the exception that the spore material is very scanty, as indeed is the case with all lean bituminous coals, in contrast to fat coking and gas coals. Fig. 12 illustrates the organization of a bituminous coal from St. Caterina, South America. The spores and lignitoid substances are as characteristically present as in the other cases. Fig. 13 shows the structure of a high-grade steam coal from Virginia. Here, as in the other cases described for bituminous coals, spores as well as lignitoid substance are found. As a final illustration, in Fig. 14 is shown a coal from Lancashire in England. The narrow stripes of lignitoid and the abundant light-hued spores can readily be discerned.

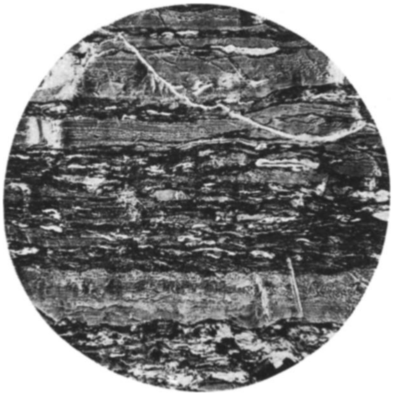
Fig. 9

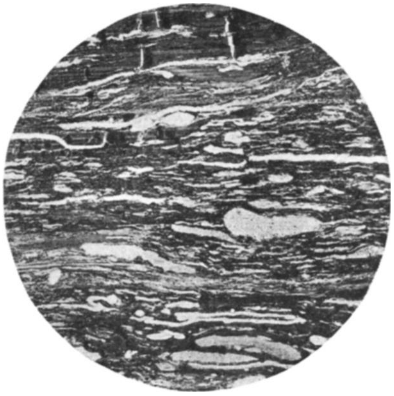
Fig. 10

Through the courtesy of the Director of the United States Geological Survey and Dr. David White, Chief Geologist, I have had the opportunity of examining nearly two hundred coals from various states of the Union and from Alaska. The results of investigation so far as bituminous coals are concerned, from whatever geological horizon obtained, showed in all instances the presence of a greater or less amount of spore material. Through the kindness of the Director of the Geological Survey of Canada, I have been able to examine into the structure of the Mesozoic coals of the Canadian West and Vancouver Island, as well as the coking and non-coking Carboniferous and Permian coals of New Brunswick, Nova Scotia, and Cape Breton Island. The results here were similar to those obtained in American coals. The coal deposits of England and Scotland have also supplied numerous and varied samples, which in all cases led to the same conclusion: namely, that spores are a practically unfailing constituent of ordinary coal. The coals of Scania (Triassic) in Sweden have yielded results in harmony with those already described for other countries and continents. Of oriental coals I have, through the courtesy of the United States Bureau of Mines, been able to examine several from Japan and China. These revealed the same unfailing spore content characteristic of other material examined. I have also examined a number of coals from both the Queensland and New South Wales coal fields of Australia, which in some cases showed a very high spore content and in all instances contained these bodies. Coals from Venezuela, Chile, Brazil, and Patagonia of various geological periods yielded similar results on microscopic investigation.

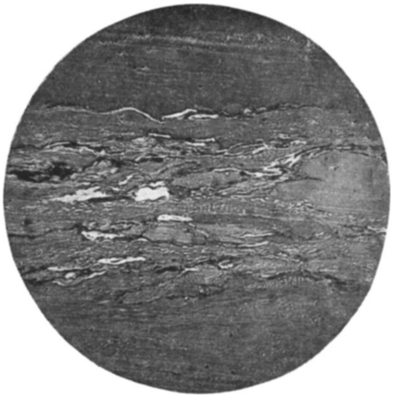

FIG. 11

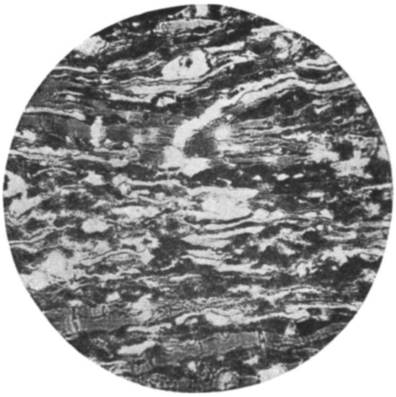

FIG. 12

The almost universal presence of quantities of spores in coals is a phenomenon not without significance in connection with our views in regard to the origin of coal substance. In the case of cannels, oilshales, and similar coals, the high spore content is interpreted on all hands as clear evidence of their formation in open water. In contrast, however, to the views held in regard to the origin of cannels and coals of similar organization are those entertained in regard to the conditions of formation of ordinary bituminous coals. These coals are regarded by the majority of geologists and paleobotanists, both in Europe and in this country, as of terrestrial origin. The reasons for this belief are drawn mainly from the strata related to the coal beds, but it is somewhat generally admitted that the character of the underclay or seatearth of a coal bed is no more final proof of its condition of origin than the cover of a book is necessarily convincing evidence as to the age and nature of its contents. It becomes clear, as a result of the microscopic examination of coals at large, that they cannot in general be derived from ordinary peat, as they do not show the structure of coals which by inclosed petrifications are known to be of peaty derivation. The paralic or old seaboard coals of Great Britain and parts of Continental Europe have a homogeneous structure, as has been shown above in the case of Westphalian coals. This homogeneity is not at all due to opacity of the thin sections, because even when quite translucent, as when prepared by the improved methods devised for the sectioning of coal, preliminarily described in the article on "Supposed Algal Coals," cited earlier in the present communication, they show no clear evidence of structure, except so far as they contain fragments of carbonized wood, a condition not uncommon in the paralic coals of British origin.

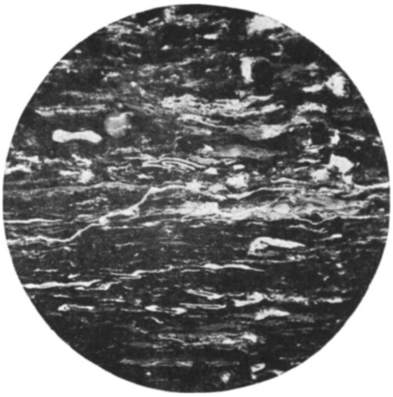

FIG. 13

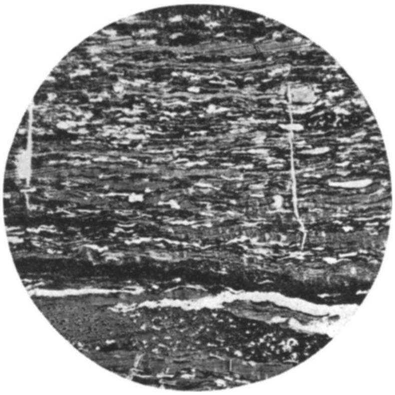

FIG. 14

Since it is generally admitted that coals containing large quantities of spores are of aquatic origin, that is, are deposited in open water, the question arises naturally, in view of the conditions described above for ordinary bituminous coals, whether they are not also laid down in open lakes, lagoons, or tranquil estuaries. There seems to be little doubt that this is the case, because not only do they show to a large extent the organization of cannels but they often pass imperceptibly into coals of this type. Moreover, an equally cogent argument is supplied by the examination of lacustrine muck of the present age. In the greatest depths of our modern lakes, which are usually of glacial origin, one ordinarily finds quantities of diatomaceous tests, or, if the region be a limestone one, a thicker or thinner stratum of a white limy deposit, containing the remains of stoneworts or Characeae. Above the basal deposits occur strata extremely rich in the pollen of conifers and certain catkin-bearing plants, such as the willow, the alder, and the birch. As the water grows shallower by accumulation of organic mud, we begin to find remains of water-lilies and other aquatics mingled with pollen. Then come layers of coarser remains of land plants, twigs, leaves, bits of wood, etc., swept by rain and winds into the lake and always more or less intermingled with a decreasing proportion of spores, until the organic silting of the waters results in the emergence of land, which if not characterizable as dry, still is able to support the growth of land plants. With the use of a peat prober of the type devised by Dr. C. A. Davis, of the United States Bureau of Mines, it is possible to recognize, by probing the depths of the bogs which vegetate on the bosoms of filled lakes, the general order of deposits outlined in the foregoing sentences. Ordinarily the depth of one of these obliterated lakes is not more than ten to twenty feet, so that we have the whole interval from the ice age to the present for the accumulation of the filling material. The estimates of the remoteness of the last glaciation vary from 25,000 years to four times that length of time. Even accepting the smallest estimate, the interval required to fill a lake ten feet in depth is great enough to call for a deposit of less than one foot of material in a thousand years, or not more than one-tenth of a foot in a century. This extremely slow rate of deposition relieves us from having to answer a stock objection to the possibility of the lacustrine formation of the raw materials of coal. It has often been pointed out that a rate of erosion necessary to fill up a large body of water in a relatively brief interval, with organic materials, would be torrential in its action. As a matter of fact, judging from actual conditions, given abundance of time, almost unlimited accumulation of vegetable remains in water, without any appreciable admixture of mineral matter, can be accounted for, particularly since vegetable substance once permanently covered by water is practically imperishable.

A very serious objection to the peat hypothesis of the origin of coal lies in the observed fact that peat bogs are not found in the parts of our present world which in their climatic warmth correspond to the probable conditions obtaining during the great coal age, the Carboniferous. Vegetable matter not continuously covered by water quickly disappears in tropical climates. True, Potonié has called attention, in his truly monumental work[1] on peat and similar formations, to the existence of what he considers to be a true peat bog in central Sumatra. The illustrations given show clearly, however, that there is present a filled body of water with trees growing upon its scarcely elevated surface. The organic material, moreover, as figured in Potonié's work, contains large quantities of pollen, thus showing its essentially open-water origin. There can be no reasonable doubt that it was as impossible for vegetable matter to accumulate on land, even on wet land, in the Carboniferous and later periods in the Mesozoic and Tertiary, as it is in subtropical and tropical climates at the present time.

We are then apparently brought to the conclusion, both from the conditions of peat formation in the present age on the one hand, and from the actual organization of the commonest and most abundant coals of every geological age and in all parts of our earth, on the other, that the raw materials of coal were heaped up, not as the result of the growth of successive generations of plants on the prostrate and persistent bodies of those already fallen, but as the age-long gradual accumulation of vegetable matter in open water. In other words, coal is not a compost heap but a sedimentary deposit. Striking as are our actual peat bogs in temperate climates, in reality they throw no light on the accumulations of vegetable matter in past ages, which have been preserved to us in the form of coal. The less conspicuous accumulations of vegetable matter in the bottoms of our existing lakes afford the real elucidation of the mode of formation of coal beds. As in our actual bodies of water, which accumulate vegetable deposits, the nature of the material laid down varies with the depth, tranquillity of the water, and other conditions, so the nature of coals derived from similar formations of past ages varies in composition. Where the spore material is more abundant, the result is a cannel or an oilshale. Where it is still plentiful but not superabundant, we have coking and gas coals as a product. Where poverty is manifest in the spore content, lean or ordinary bituminous coals are formed. The processes of devolatilization leading to the formation of anthracites and similar high-grade coals will not be considered in the present connection.

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[1] *Die Recenten Kaustobiolithe u. ihre Lagerstaetten*, Berlin, 1908–12.